Experimental results on the free cooling power available on 4K pulse tube coolers

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Abstract. We report experimental results on the free cooling power available at the level of the second stage regenerator of a 4K pulse tube cooler. By using two localised heat exchangers we obtained additional cooling power, in the range 400 and 600 mW at 4.8 K or between 500 and 700 mW at 18 K. We have investigated in detail the thermal behavior of the system. In this manuscript we report on the evolution of the temperature of the heat exchangers and the pulse tube stages under different distributions of the total heat load.

1. Introduction

In order to optimize the design of a complete cryogen-free system, for instance a cryocooler and an associated dilution refrigerator unit, it is essential to characterize the cryocooler performance. This means establishing the cooling power available at the level of all the stages of the cryocooler, as well as their temperature, for different heat loads on the stages. In the example given here, the usual two main cooling stages, and two additional ones ("intercepts") are used. The intercepts allow recovering additional cooling power, as suggested by Zhu *et al* [1]. The concept gave rise to a practical demonstration and application by the authors, at Air Liquide and CNRS [2, 3, 4]. Our studies led to the optimization of the cryocoolers performance and the realization of highly efficient cryogen-free dilution refrigerators [2, 5, 6]. Related measurements were made at Cryomech [7] following the request of Air Liquide [8]. The properties of a heat exchanger for the thermalization of the mixture in pulse tube based dilution refrigerators have been discussed by Uhlig [9, 10], in a series of particularly interesting articles. We present in the following the main results of our characterization of the additional power available on a pulse tube cryocooler with heat intercepts.

2. Experimental set-up

We have used a pulsed-tube cryocooler model PT-405 manufactured by Cryomech [7]. The cooling power available at the first stage of this machine is 25 W at a temperature on the order of 60 K. The most relevant parameters for dilution refrigeration and many other applications are the power available at the level of the second stage of the pulsed-tube, and the corresponding temperature. For the model PT-405, the second stage cooling power is 0.5 W at 4 K. In order to benefit from the cooling power available at the level of the regenerator, two copper heat exchangers were installed on the stainless steel tube connecting the two main stages of the cryocooler. These intercepts (figure 1) are made from a plate of thickness 5 mm, with two

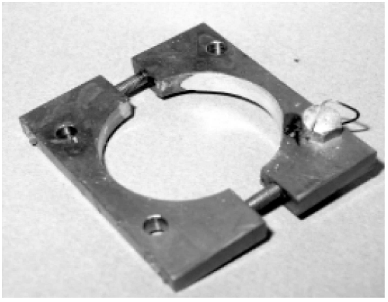

Figure 1. Copper heat intercepts, placed on the pulse-tube cooler between the first and second stages as indicated on figure 2.

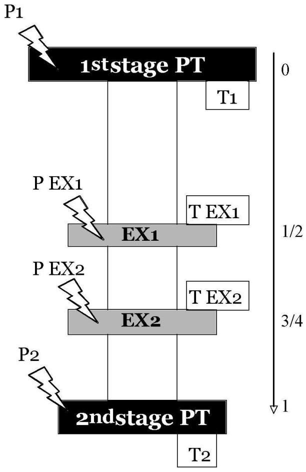

Figure 2. Pulse-tube 1st and 2d stages and 2 heat intercepts.

separate parts tightened by brass screws. Indium was used to improve the thermal contact between the heat exchangers and the stainless steel tube. The intercepts have been placed at convenient positions along the tube (towards the low temperature side), as shown on figure 2. Calibrated carbon and germanium resistance thermometers were placed on the 2 main stages and the 2 intercepts to determine their temperature (respectively T1, T2, T EX1, T EX2). These temperatures were controlled by TRMC2 temperature controllers [11] by applying power (respectively P1, P2, P EX1, P EX2) on electric heaters.

3. Power measurements

Even without the intercepts, the two stages are not decoupled (it is favorable to keep a heat load on the first stage). The temperatures of the 2 main stages as a fuction of the power applied on both stages (power curves) T1(P1, P2); T2(P1, P2) are provided by the manufacturer, and they have also been checked for our machine. For the measurements presented here, the temperature of the first stage (T1) was kept constant (regulated) at 60 K. The temperature of the second stage (T2) was then 3.5 K, and subsequently T2 was regulated at 4, 4.5 and 4.75 K. We then applied power to the first intercept (P EX1), while measuring the cooling power of the second stage P2 and the temperature of the intercepts (T EX1 and T EX2). The same procedure was repeated, applying power to the second intercept (P EX2). These measuremnts were made for different temperatures of the second stage (T2). The results are shown on figures 3 and 4. In these graphs, the cooling power of the second stage is normalized to that measured without power on the intercepts (P2-0) : 0.25 W at 3 K, 0.5 W at 4 K, 0.65 W at 4.5 K and 0.75 W at 4.75 K. There is clearly a critical power on the order of 700 mW, below which the performance of the cryocooler remains unaffected, and this “free power” is obviously of interest.

We present on figures 5 and 6 the temperature of the intercepts (T EX1 and T EX2) as a function of the applied power. The solid curves and symbols give the temperatures of an intercept when power is applied on the same intercept, while the dashed lines and open symbols give each intercept temperature when power is applied to the other intercept. An instability is observed when the first intercept temperature T EX1 exceed 18 K, and the second intercept temperature T EX2 exceeds 4.8 K. Again, there exists a large power range where the cryocooler performance is interesting.

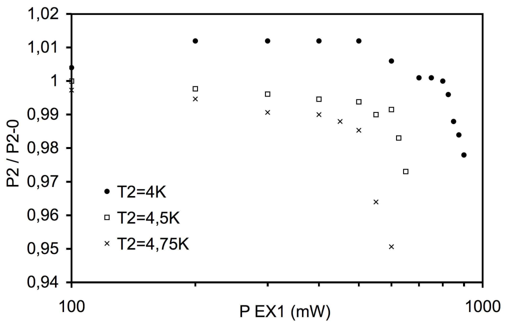

Figure 3. Normalized cooling power of the second stage, as a function of the power P EX1 applied to the the first intercept, for different temperatures T2 of the second stage.

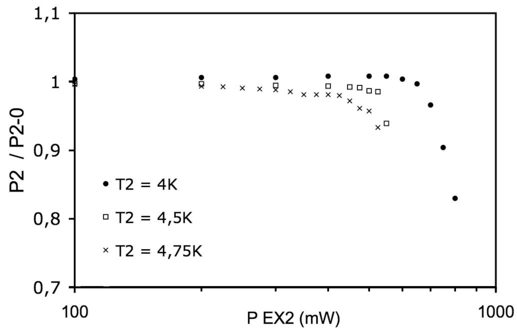

Figure 4. Normalized cooling power of the second stage, as a function of the power P EX2 applied to the the second intercept, for different temperatures T2 of the second stage.

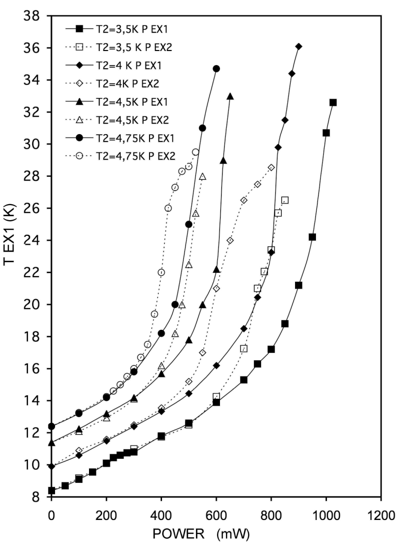

Figure 5. Temperature of the first intercept T EX1 as a function of the power P EX1 applied to this intercept (solid lines and symbols), or to the second intercept PEX2 (dashed line and open symbols) for different temperatures T2 of the second stage.

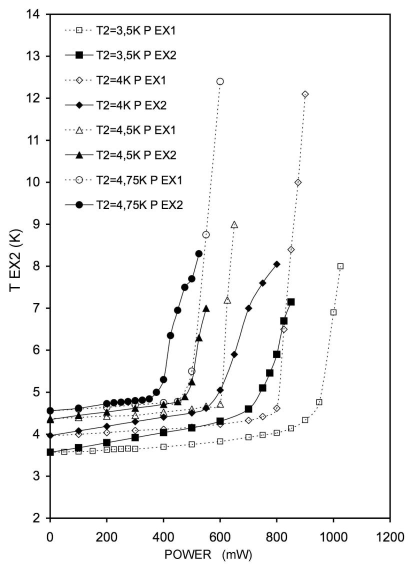

Figure 6. Temperature of the second intercept T EX2 as a function of the power PEX2 applied to this intercept (solid lines and symbols), or to the first intercept P EX1 (dashed line and open symbols) for different temperatures T2 of the second stage.

We finally investigated how a power distribution among the two intercepts affected the thermal behavior of the system. For this purpose, we kept T2=4.5 K, we applied a power of 400 mW to the first intercept (EX1), and we increased the power on the second intercept (P EX2) by steps. The results for the temperature of both intercepts for different distributions of

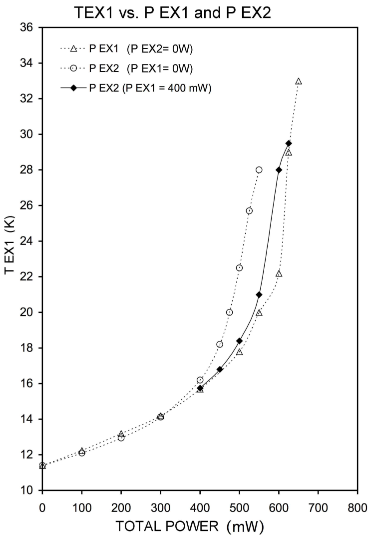

Figure 7. Temperature T EX1 of the first intercept as a function of the total power applied on both intercepts; see text

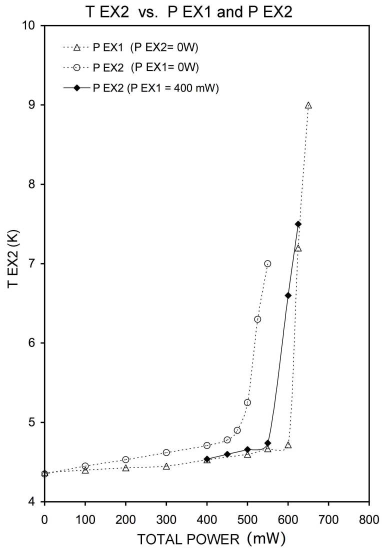

Figure 8. Temperature T EX2 of the second intercept as a function of the total power applied on both intercepts; see text

the applied power are shown in figures 7 and 8. The first intercept admits 400 mW at 18 K while the second one admits 125 mW at 4.8 K simultaneously. Similar measurement done with 300 mW on EX1 give 500 mW of combined power, with 200 mW added on EX2 before reaching the system instability.

4. Conclusion

The data presented here on the "free cooling power" obtained for two intercepts placed between the first and second stage of a pulse-tube cryocooler constitute a valuable tool for the design of cryogen-free refrigerators, in particular for applications where the second stage temperature must be kept as cold as possible and should not be used for precooling or thermalizing directly current leads, support rods, incoming helium flow, etc. The intercepts provide additional cooling power which can be used to alleviate the task of the second stage of the cryocooler.

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